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Original Article

AGING BEHAVIOUR AND TENSILE STRENGTH OF MARAGING STEEL PROCESSED BY LASER WELDING

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ABSTRACT

Maraging steels find a considerable number of applications in aerospace, defense, and automobile industries. In view of this, the maraging steel grade 300 is considered for analysis. This material is an iron-nickel alloy that derives strength basically from the intermetallic precipitates generated during the aging process. The material possesses good weldability in solution annealed condition. Therefore, prior to aging, the samples were laser welded. The aging cycle was then subsequently applied to improve the strength and the hardness of the weldments. In the precipitation hardening, the heat treatment parameters play a vital role in deciding the mechanical properties. The various parameters that are involved in the process are, viz., i) Temperature ii) Soaking time iii) Heating rate and iv) Cooling rate. However, as the heating rate and cooling rate have a negligible effect on the mechanical properties, temperature and soaking time are considered as the variables in the work. Different temperatures and aging times are considered to find the strength of the laser weldments.

KEYWORDS: Laser Welding, Maraging Steel, Aging, Precipitates, Strength & Hardness

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INTRODUCTION

Maraging steels are a group of martensitic steels with low-carbon and high-nickel content. The name comes from the concoction of the two terms, "**mar**tensitic" and "**aging**", as the soft martensitic phase is subjected to aging heat treatment to immensely improve hardness and strength. Maraging steels are characterized by a high number of alloying elements, mainly Ni, Co, Mo, Ti, and Al, which are added to promote and produce intermetallic precipitates. These steels exhibit excellent mechanical properties, combining greater strength with better toughness. The strength of maraging steels mainly depends on three things, which are: the strength of martensite matrix, solid-solution strengthening, and precipitation hardening. A strength of the martensite matrix depends on carbon content, and the solid solution strength depends on the solute atoms. Out of the above three parameters, the precipitation hardening contribution is the most significant to the strength of the maraging steel as the maraging steel possesses virtually no carbon content and a very soft and ductile martensite. Basically, maraging steels are low carbon content steels which derive their strength not from carbon content but from the intermetallic compounds present in the material.

Precipitation kinetics are mainly influenced by aging temperature and aging time, thus the strength and hardness of the maraging steels are the functions of aging temperature and aging time. Depending upon the progressive aging temperature and aging duration, the material is subjected to definite microstructural changes

which in turn affect the mechanical properties of the material. The primary step in precipitation hardening is aging of the material at the temperature less than the solidus temperature followed by quenching.

LITERATURE SURVEY

Zhu et al.[1] investigated the microstructural evolution of maraging steel C300 in the aging temperature ranging from 400 to 600^{0}C through Monte Carlo simulation and the modeling was validated by the experimental results. The relation between the mechanical properties of C300 and its precipitation behavior was studied. Sakthipandiet al.[2] established a setup for observing the microstructural changes in M250 through in-situ ultrasonic measurements. The microstructural changes were observed over the temperature range of ambient temperature to 1200K.Liu et al. [3] investigated the effect of aging on the properties of a maraging steel. It is observed that the yield strength obtained based on a revised Orowan mechanism was is in close agreement with the practical data. The microstructure and the mechanical properties of *CORAX* maraging steel were studied by Höring et al. [4] up to 300 h at 798 K. It was noted that during aging, the strengthening of maraging steel was caused by the formation of an intermetallic phase enriched in Ni and Al which has an ordered B2 (CsCl) superlattice structure. Dilatometric studies were made to find the phase transformations in 300 and 350 maraging steel at different heating rates of 1, 10 and 28 °C/s. It was shown that the precipitation mechanism was happened by lattice diffusion. It was further observed that Co and Ti contents greatly the affects the precipitation [5].

Pardal et al [6] studied the precipitation hardening behavior of an 18Ni-Co-Mo-Ti maraging 300 in the 440^{o}C-650^{o}C. The aging at different temperatures was modeled by using an expression derived from Johnson-Mehl-Avrami (JMA) equation. The activation energy for precipitation was found and a comparison with the published values was made.Park et al [7] studied the reversed austenite transformation and existence of retained austenite during tempering of the super martensitic stainless steel of Fe-14Cr-7Ni-0.3Nb-0.7Mo-0.03C based on microstructure and X-ray diffraction, and tensile and hardness tests. Acicular type retained austenite was found at the lath boundary of martensite with the interior appeared after solution annealing. The magnetic properties and hardness of a Ni–Co–Mo–Timaraging steel 300 grade were measured as the function of aging temperature by Pardal et al [8].

The austenite and martensite phase quantifications in the different heat treatment conditions were carried out by X-ray diffraction using direct comparison method. Viswanathan et al. [9] examined the sequence of austenite reversion during averaging in 18 Ni (350) maraging steel and its effects on the mechanical properties. Austenite with different morphological features was identified at different stages of averaging. The influence of homogenization and the revolutionization on an 18Ni(300) maraging steel weldments were evaluated by FANTON [10]. The effects of laser welding and post-weld heat treatments were analyzed. Homogenization treatment showed to be effective in eliminating the as-cast dendritic structure of the fusion zone but decreased the yield strength.

EXPERIMENTATION

In the present work, the laser weldments were subjected to precipitation hardening as per the heat treatment parameters are given in Table. The aging temperatures considered are below the solidus temperature at which lower solubility of the material enables the generation of the precipitates through diffusion process from the supersaturated solution. Since the supersaturated solution is not stable, sufficient time has to be given for the precipitates to grow. The aging times are chosen considering the above factor. The furnace with the following specifications was used for heat treatment: Maximum temperature – 1250^{0}C, Operating temperature – 1200^{0}C, Heating element – Kanthal (4kW),

Programmer – Nippon Segments Programmable Controller Thermocouple – K-type, Thyristor – 3 Phase with 27A, Accuracy – 1^0C, Power – 4kW, 3 Phase AC.

The aging time was varied from 4 to 10hrs with the step size of 2hrs while the temperature was considered at 440^0C,480^0C and 510^0Cand respectively. This has led to the total combinations of 12 samples as shown in Table 1. Depending upon the combination of time and temperature, each sample undergoes systematic microstructural changes. Hence the experimental investigations were made to find the optimal combination of aging temperature and aging time at which the maximum strength takes place.

Table 1: Heat Treatment Parameters

Temp/Time	4 Hours	6 Hours	8 Hours	10 Hours
440 o C	Sample 1	Sample 2	Sample 3	Sample 4
480 o C	Sample 5	Sample 6	Sample 7	Sample 8
510 o C	Sample 9	Sample 10	Sample 11	Sample 12

The sample was placed in the furnace once it was heated to the specified temperature. Then it was held at that temperature for the prescribed aging time. Once the sample was held for the specified time, it was then cooled in normal air to room temperature. To consider only the effect of the aging parameters, all the samples were welded at the same process parameters. The process parameters at which the laser welding was performed were as follows: Pulse frequency – 18Hz, Pulse width – 11ms, Welding speed – 75mm/min, Pulse energy- 16J.

RESULTS AND DISCUSSIONS

The welded samples after the age hardening process were tested for their tensile properties of ultimate tensile strength. A tensile test is a widely used method to ascertain the strength of a welded joint. The specimen for each test was cut in the transverse direction to the weld. It is seen that the specimen comprises the fusion zone, heat affected zone, and the base material. The transverse welded specimens were prepared as per the ASTM E08 standards. Three such specimens were prepared for each test and the average of the results obtained for each specimen is recorded as the output. The tensile test was performed on the Instron100-kNcapacity universal testing machine having the pneumatic grips for accurate alignment of the fixtures. The constant strain rate of 0.50 mm/min was used during the test and the test was conducted at the room temperature.

The obtained values of the ultimate tensile strength are shown in Figure1. The improvement achieved in the strength is explained considering the scanning electron micrographs (SEM) shown in Figure 2-13.

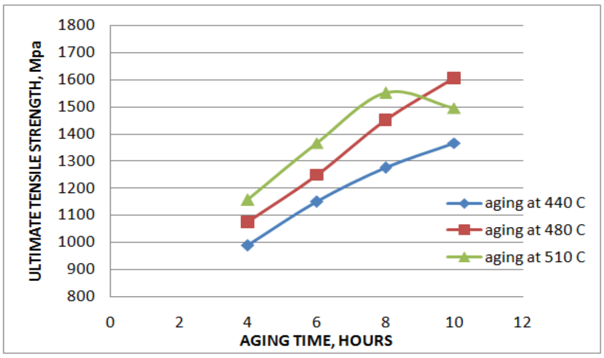

Figure 1: Obtained Values of Tensile Strength

AGING AT 440 ^{0}C

At 440 ^{0}C, the specimens were aged at four time periods, viz., 4h, 6h, 8h and 10 hours. It is observed from Figure 2-13 that the tensile strength was increased in proportion to the aging time as the size and the population of the precipitates grows with respect to the aging time.

Figure 2: It shows the corresponding scanning electron micrographs when the maraging steel C300 samples were heat treated at 440 ^{0}C for four hours. As it is observed from the Figure2, no detectable precipitates were formed during the process as the aging temperature and the time was not sufficient to produce them. The tensile strength of the chosen material is almost same as that of the as-welded condition. At this condition, the material has the tensile strength of 997MPa. The lath martensitic structure was found to be intact during the heat treatment process.

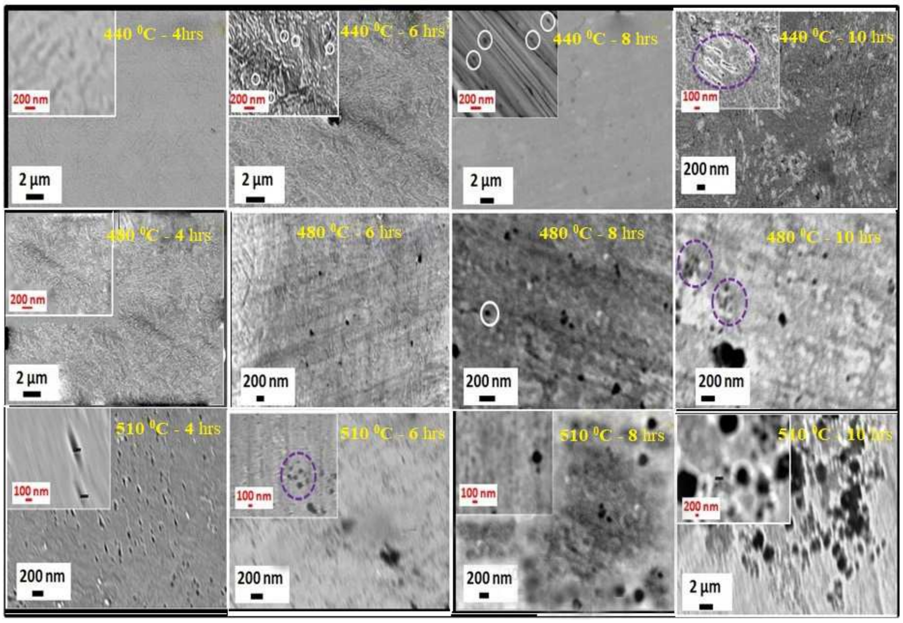

Figure 2-13: SEM Images of Aged Samples at Different Aging Conditions

Figure3: It exhibits the micrograph when aging was carried out at the temperature of 440 ^{0}C for 6 hours. This combination of parameters initiated the precipitates formation. These intermetallic precipitates tend to form if the metal percentage in the matrix exceeds the solubility limit at low temperature during quenching. The precipitates were confirmed through the EDS analysis. The EDS analysis, in Figure 14, indicates that the precipitate is comprised of Ni and Mo phases. Because of the presence of the Ni and Mo phases, it is drawn that the precipitates formed are of Ni_3Mo. The precipitates are found to have their sizes around 20nm. These Ni_3Mo initial sites of precipitates might be formed due to the diffusion transformation of Ni and Mo alloying metallic phases in the martensitic matrix.

Figure 4: Isothermal aging at 440 ^{0}C temperature of the welded samples for 8 hours accelerates the precipitation behavior of intermetallics in the martensitic matrix. Precipitate coarsening happens in aging for long periods, this behavior causes the conversion of the initial nucleation sites of intermetallics to fully developed precipitates of size nearly equal to 30 nm. Large numbers of precipitates which are coherent with the matrix resulting less spacing between the precipitatesare observed in the Figure 4.These closely distributed submicron precipitates in the matrix impede the dislocations motion in the base metal leading to a great improvement in the strength. Owing to this, the strength varies in proportion to the aging time. Thus aging at 8 hours, has incurred the stress of 1290MPa.

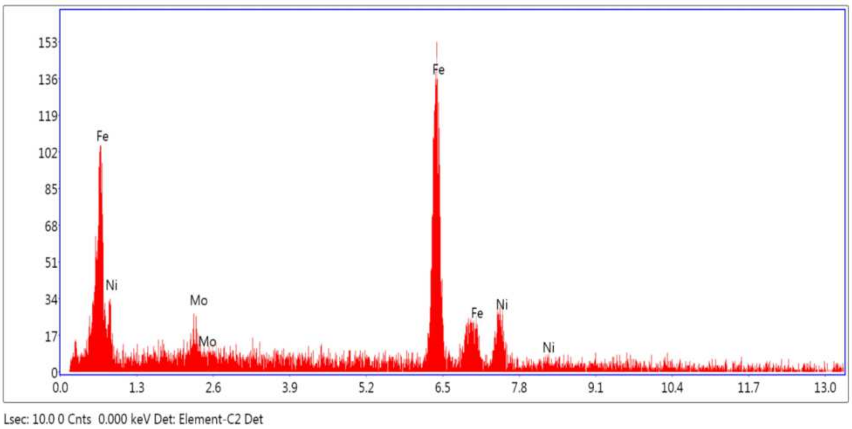

Figure 14: EDS Graph to Confirm the Precipitate

Figure 5: Further aging for 10 hours causes precipitate coarsening and on the other hand the uniformly distributed precipitates tend to form clusters in the matrix. At this prolonged aging period, aging results in accelerated coarsening of precipitation and as result of that precipitates of size nearly of 500 nm as observed in Figure 5.

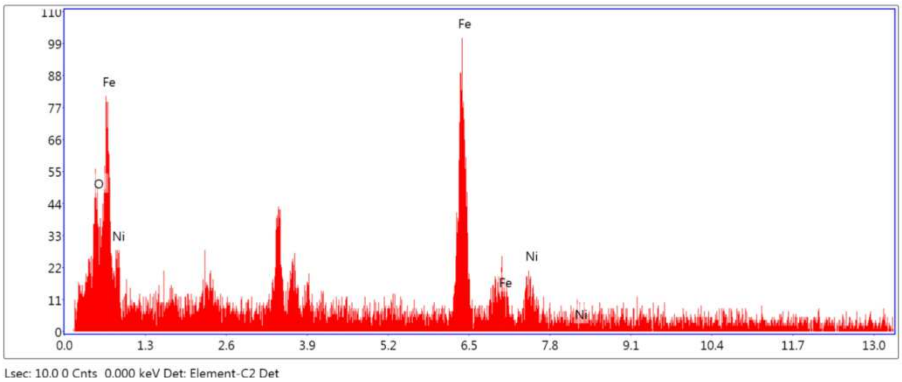

Figure 15: Phases Present in the Selected Area of White Spot for EDS Analysis

AGING AT 480 ^{0}C

The maraging steels aged at 480°C shows a linear relationship between the strength and the aging time. While keeping samples longer at this temperature, the tensile strength continues to increase without any sign of averaging.

Figure6: The microstructure images of the samples aged at 480 ^{0}C for 4 hours exhibit no detectable precipitates in the martensitic structure. However, a little improvement in the strength is found due to the probable precursor forms of the precipitates.

Figure7: The precipitates are of nickel-rich intermetallic phases, and Mo as the secondary phase metal in precipitate as it is evident from the EDS analysis shown earlier. This aging process mainly aimed to form a uniform distribution of fine nickel-rich intermetallic precipitates during the aging of the martensite. These precipitates serve to strengthen the martensitic matrix. These precipitates in the martensite structure increase the strength from as-welded condition. In the present case, when aged at 6hrs, precipitates were observed having the approximate size of 20nm though they are in lesser in number.

Figure 8: Aging at this temperature 480 ^{0}C for 8 hours causes further coarsening of the precipitates already present in the metastable martensite. The increased number of precipitates in the material made the material stronger as it

reaches the strength of 1260MPa. Aging of maraging steel samples at the considered combination of the aging time and the temperature causes dislocation of precipitates to form groups. The intermetallic phases of some submicron level particles dissolve in the solid solution of martensite at long aging hours, this behavior is just initiated in the sample aged at these conditions. Simultaneously the metastable martensite starts reverting into unstable austenite phases. Because the austenite reversion is in its early stages, it has not shown any considerable effect on the strength increment leading to improvement in the strength to.

Figure9: Aging of maraging steel samples at 480 ^{0}C for 10 hours slightly overages the material. Coarsening of the precipitates at some locations, dissolving of precipitates in some locations and reversion of metastable martensite to austenite at some locations took place in the samples. As it was evident from the figure 9, coarse precipitates of 500 nm and large white patches of reverted austenite were observed in the microstructure. Though the austenite reversion took place, the strengthening mechanism due to the coarse precipitates dominates the effect of austenite reversion in the material, thus the strength reaches a peak value of 1600MPa.

AGING AT 510 ^{0}C

Aging of maraging steels at this temperature is considered high-temperature aging. To study the microstructural characteristics of aging behavior of maraging steels, welded samples were heat treated at 510 ^{0}C for four different aging times of 4h, 6h, 8h and 10 hours.

Figure10: Aging of the samples at 510^{0}C for 4 hours, as observed from Figure10, generated the lath shape precipitates rather than the spherical shaped ones. The precipitations of a very fine needle or rod-shaped precipitates are clearly observed in the Figure10At this aging time, the precipitates of needle shapes having the size closely to 25nm are found to be uniformly distributed in the matrix. No austenite reversion took place as observed from the Figure 10.

Figure 11: At the aging parameters of 510 ^{0}C and 6hours aging, the coarsening and the clustering of the precipitates took place. The precipitates are grown to the average size of 100nm. Not considerable austenite reversion was found.

Figure 12: Aging parameters of8hours and 510 ^{0}C caused further coarsening of the precipitates. The precipitates took the size of 150nm approximately. Though more reverted austenite was observed when compared to the previous case, the strengthening due to larger size of the precipitates has dominated to impart the better strength to the material. At this set of aging parameters, the material has attained the maximum values of the strength.

Figure 13: High- temperature aging for 10 hours is considered averaging as it leads to larger reversion of austenite in the matrix phase and dissolution precipitates in the martensite. With the increased temperature the solubility limit of Ni and Mo increases in the base metal leads to the homogenous structure with no precipitates in the material. averaging results in undue coarsening of the lath shape precipitates. In Figure 13, a lot of white patches representing the reverted austenite were observed. The strength has been reduced drastically at this combination of parameters. This downfall in hardening is attributed essentially to the formation of reverted austenite rather than the precipitate coarsening. The amount of reverted austenite has been found to be overfilled. This neutralizes the strengthening gained with the growth of the precipitates. In addition, at this high-temperature aging at the prolonged period, smaller precipitates get dissolved in the matrix. Because of the dominant nature of the reverted austenite combined with the disappearance of the smaller precipitates, the strength has gone down drastically.

CONCLUSIONS

- The present work investigated the aging behavior of the maraging steel grade 300 at different aging conditions. The aging time was considered at 4,6,8, and 10hrs while the temperature was considered at 440^0C,480^0C and 510^0C respectively. Prior to aging, all the maraging steel samples were laser welded.
- The strength of the laser weldments was measured at all the combinations of the different aging conditions.
- It is observed that during aging, the size and the percentage of precipitates grow. However, they annihilate at higher aging conditions.
- Reverted austenite was also observed at elevated temperatures. In practice, the reverted austenite should be minimized as it is detrimental to any kind of strength.
- The present work reveals that optimal strength of the maraging steel laser weldments is achieved at the aging temperature of 480^0Cand aging time of 10hrs

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